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ARCTIC METEOROLOGY RESEARCH GROUP
McGILL UNIVERSITY
MONTREAL

Water Balance and Heat Flux of the Arctic Ocean

by

E. VOWINCKEL and SVENN ORVIG

PUBLICATION IN METEOROLOGY No. 44 | *September 1961*

SCIENTIFIC REPORT No. 1

under

Contract No. AF 19 (604)—7415

Prepared for

GEOPHYSICS RESEARCH DIRECTORATE
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PREFACE AND ABSTRACT

The present report forms part of a study of the heat balance of the Arctic. It became necessary in this investigation to examine the existing literature on the water balance and heat flux into the Arctic Ocean.

As contributions to this subject are found in a great number of different publications, and as a large proportion is in Russian and not easily accessible, it seemed worth-while to summarize the available information as completely as possible.

The investigation was not undertaken for oceanographic purposes but for heat balance calculations. Therefore, all the more detailed oceanographic material was disregarded, such as different water masses and stratification. However, much of this material will be found in the literature cited.

When calculating the heat content of the various water masses, the specific heat of the water has been taken as 1 $^{cal}/g$, degree and the density as 1 $^{g}/cm^{3}$. This seems, from the literature examined, to be the Russian custom. In reality, the specific heat of Arctic Ocean water is closer to 0.94 $^{cal}/g$, degree and density 1.03 $^{g}/cm^{3}$.

As the available information on mass transport and water temperatures is sporadic and not accurate in detail it was considered, for the present, satisfactory to use the more convenient values. The inaccuracy will amount to about 3%.

The text defines the use of the terms "Arctic Ocean" and "Polar Ocean" and then goes on to discuss mass flux and temperatures for the various ocean currents into and out of the Arctic. Runoff and precipitation are also discussed.

Ice export by the various currents is then treated, and the heat gain by formation and export of sea ice is calculated. Finally, water balance and heat flux estimates are given for the Arctic and Polar Oceans, with the annual total heat gain, including that of ice.

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THE ARCTIC OCEAN

Water Balance and Energy Flux

In the oceanographic literature two boundaries are used for the Arctic Ocean:

1. Arctic Ocean as used by Sverdrup (1954): Eurasian coast - Bering Strait - coast of North American continent (excluding Hudson Bay) - coast of Greenland - Denmark Strait - Shetland Islands - Norway. The area by this definition is 14,090,000 km^2.

2. Arctic Ocean as frequently used by Russian authors: as under (1), but from Greenland to Spitsbergen - north Novaya Zemlya - east coast of Novaya Zemlya to mainland. This area amounts to 9,906,000 km^2. To avoid confusion, this area will in the following be called "Polar Ocean".

The Polar Ocean therefore comprises the Arctic Ocean less the Norwegian Sea (2,705,000 km^2) and Barents Sea (1,479,000 km^2).

Method of Calculation

The general method for the calculation of energy obtained or released by the ocean is to observe the energy in- and outflux for a given area. For this purpose the temperature and velocity profile to the sea floor must be known. If these elements were given for a sufficient number of ocean stations, maps could be constructed and for each desired area the energy balance could be obtained. However, observations are far from sufficient for such an undertaking. Especially are velocity observations or calculations lacking. The available data permit the best statements to be made about in- and outflux through the relatively narrow straits.

The Arctic Ocean is in this respect in a rather favourable position, as it is a mediterranean ocean borded by continents with relatively narrow connections to the open ocean. Furthermore, a subdivision between Arctic and Polar oceans is possible. About the interior of the Arctic Basin and its marginal seas very little can so far be said with reasonable certainty.

The in- and outflux values and the mean temperatures are discussed individually in the following.

I. ATLANTIC OCEAN

The warm current entering from the Atlantic Ocean is by far the most important source as far as water volume and heat is concerned. The main portion of this water flows through the Faeroes - Shetland Channel, and only minor portions between Faeroes and Iceland and, as the Irminger Current, on the west side of Iceland. Unfortunately, observations and estimates about this most important current are highly contradictory.

Sverdrup (1954), when giving a water balance for the Arctic Ocean, considers only the waters entering the Arctic Ocean to the north-west of Shetland, respectively groups together all net influx under this heading, and obtains 3.0×10^6 m^3/sec or 94,608 km^3/year. The same figure is quoted by Dunbar (1960).

Jacobsen (1943) studied the flux through the Faeroes - Shetland Channel along two sections with 24 individual crossings during 1902-1939. His result for the period May - September is 15.2 resp. 11.9 km^3/hr, depending the method of calculation used (133,000 and 104,000 km^3/year).

More recent is the investigation by Tait (1957), covering the years 1937-1952. The following figures summarize his results about the flux determinations for the Faeroes - Shetland Channel.

km^3/hr

	Maximum Flow	Mean Flow	Minimum Flow	No. of Years
Jan.	-	-	-	-
Feb.	-	11.9	-	1
Mar.	15.7	12.5	7.3	3
Apr.	-	4.8	-	1
May	13.6	6.3	2.4	8
June	19.6	9.0	3.3	10
July	15.8	8.6	2.3	6
Aug.	5.0	3.5	2.7	5
Sept.	11.2	10.6	10.0	2
Oct.	-	10.8	-	1
Nov.	14.1	12.4	10.8	3
Dec.	-	23.4	-	1

The yearly flux would be approximately 10.3 km^3/hr or 90,228 km^3/year. This value is significantly smaller than Jacobsen's. If from Tait's results the maximum values are chosen (for the months with more than one year's observation), the mean flux would come to 13.6 km^3/hr or 119,136 km^3/year. This would be in better accordance with Jacobsen's results. It must be considered, however, that Tait's calculations are probably based on better observational values from more recent years.

As mentioned above, a certain amount of atlantic water does not flow through this channel, but to the north-west of the Faeroes and to the west of Iceland in the Irminger Current. The amount of this flow is again estimated rather differently by the various authors. Hermann (1949) concludes that the inflow into the Norwegian Sea from northwest of the Faeroes is of the same magnitude as the influx through the Shetland Channel. Tait states that this flux was found to be 1/4 of the channel flux, four times in 1949 and once in 1950. Other instances, with fluxes outside the channel even reaching the same value as the channel flux itself, are recorded for 1951 and 1952. No systematic investigations of this matter are available and therefore, as a tentative assumption, it will be taken that 25% of the flux in the channel are found outside it. This would bring the total flux with Jacobsen's observations to 166,000 resp. 130,000 km^3/year, and with Tait's mean figure, 113,000 km^3/year.

Dietrich (1957) investigated a cross-section somewhat to the south, at 60°N. He obtained for June 1955 for the region between the mid-atlantic ridge and Shetland, between surface and bottom, a net northwards transport of 6.8×10^6 m^3/sec or 214,445 km^3/year. A considerable proportion of this water turns westward again and merges with the East Greenland Current and therefore is not transported into the Arctic Ocean. If only the flux east of 25°W is considered, the northward flux will be 113,530 km^3/year. If it is further considered that the June flux is, according to Tait, about 10% below the yearly average, the observations of Dietrich lie between Jacobsen's and Tait's results.

Timofeev (1956), using Russian sources, presents the following figures:

Atlantic influx:	400,000	km^3/year
outflux:	248,000	"
net gain:	+152,000	"

He claims that his results is a long-term average. Treshnikov (1959) estimates this net flux to be 128,500 km^3/year. Shokalskii (1933) gives the flux as 140,000 km^3/year. Timofeev (1960), quoting different Russian authors, gives for the total flux into the Norwegian Sea as much as 213,000 km^3/year, a value far higher than all other estimates.

A large number of observations are available of the temperature of this current. Sverdrup (1954), after Helland Hansen, gives a mean temperature of 8°C. Model (1950), repeated (1955/56), basing his calculations on 1,600 observations on 160 profiles, arrives at +7.5°. Jacobsen (1943) gives +6.7°. Dietrich's (1957) temperature and velocity cross-sections indicated for June about +9°. Unfortunately, Jacobsen's figures do not lend themselves to a calculation of the mean heat flux. Timofeev (1960) gives the annual influx of heat into the Arctic Ocean as 1,734,000 x 10^{15} cal. With his influx figure of 213,000 km^3/year his mean temperature would be 8.1°, very near the values given by the other authors.

However, as the atlantic influx is by far the largest in volume, and hence the most important in heat transport, even small differences in temperature make a significant difference to the total. The best substantiated values seem to be +7.5° and +8.1°. It seems advisable at the present stage to adopt the mean between the two, i.e., 7.8°C.

II. BERING STRAIT

For this strait several independent investigations are available. Sverdrup (1954) quotes an influx of 0.3 x 10^6 m^3/sec, basing his results on observations by the U.S. Coast Guard (1936), who observed a flux of 0.88 x 10^6 m^3/sec, after a continuous summer recording for 21 hours. Sverdrup reduced this figure drastically, as he believed that during winter the flux is much less. A further estimate originates with Zubov-Karelin (after

Gordienko 1958), giving 20,000 km^3/year. This is probably based on investigations by Zubov (1948) or Wolkov (after Timofeev 1960), who obtains 20,000 resp. 20-22,000 km^3/year, which, however, is regarded by Timofeev as too low. Timofeev (1960) quotes as the most reliable calculation, based on evaluation of data up to 1943, the one by Basakov. He gives the following table of the water and heat flux:

	Water Flux km^3	Heat Flux in cal$\times 10^{15}$
Jan.	2,218	- 3,992
Feb.	1,752	- 3,154
Mar.	1,333	- 2,300
Apr.	1,542	- 2,776
May	2,023	- 2,553
June	3,036	+ 1,091
July	4,296	+11,060
Aug.	5,142	+14,750
Sept.	4,884	+21,748
Oct.	3,894	+ 7,012
Nov.	3,247	- 2,796
Dec.	2,758	- 4,600
Year	36,125	+33,490

(Negative heat flux indicates flow of water at a temperature less than 0°C.)

A further investigation, taking into account many stations with flux observations, originates with Maksimov (1944). He obtains for the summer months a flux of 4,100 km^3/month and for winter 369,800 m^3/sec. He calculates the annual flux on the assumption of summer flow for the ice-free months, an intermediate flow for the montns with some ice, and a winter flow for complete ice coverage. The annual influx derived in this way is 30,354 km^3. His assumption of the dependence of the flux on the ice cover seems realistic as the bulk of the flux takes place near the surface layers.

Coachman and Barnes (in press), after discussing the Russian and more recent American observations, obtain a yearly influx of 1 x 10^6 m^3/sec or 31,536 km^3/year; a figure very near the one of Maksimov. Treshnikov (1959), without further reference, estimates the flux again rather high with 37,500 km^3/year.

Sverdrup (1954) estimates the mean heat content of the current as zero. This seems unrealistic when consulting the surface temperature distribution and cross-sections given by Lafond (1954), with temperatures in summer in the upper 30-50 m of over 6° and below that depth of 1°. When converting the heat flux figure of Basakov into temperature, a mean temperature of 4.45° is obtained for September, the month with the highest temperature, and the annual mean would be 0.93°. These figures seem to be more in line with the actual temperature observations published so far.

III. RUNOFF

A not insignificant source of water and heat for the Arctic Ocean is the runoff from the rivers. Timofeev (1956) uses the figure 4,400 km^3/year, while Sverdrup (1954) quotes 5,000 km^3/year. Gordienko (1958) gives the significantly lower figure of 3,000 km^3/year. On the American continent only the Mackenzie River is of importance. Estimates of the flux are made by Mackay (unpublished), giving for the summer the magnitude of 12,000 m^3/sec and for winter substantially less. Antonov (1936) studied the outflux into the Kara Sea. He found the total flux to be 1,000 km^3/year. (Ob 440, Yenisei 410, Tazovskaya Gulf 58, Taimyr Peninsula 47, Baidaratskaya Gulf 13, bays of Ob and Gydaiamo 32 km^3/year.) In 1958 Antonov revised and extended his figures as follows:

Yenisei	598 km^3/year
Lena	511 "
Ob	430 "
Mackenzie	430 "
Kolyma	132 "

For the whole continental drainage into the Arctic Ocean he gives the following results;

Northwest Scandinavia, extreme NW of USSR	153 km^3/year
European USSR, excl. Pechora	359 "
Siberia, inc. Pechora	2,442 "
North America, incl. Yukon	1,053 "
Greenland (tentative estimate)	373 "
	4,380 km^3/year

From this figure has to be deducted the Yukon River with 240 km^3, flowing into the Bering Sea, and the Greenland figure, as this export will mainly consist of ice with low temperatures; this would leave an influx of 3,767 km^3/year.

In Antonov's results it is interesting to compare for Siberia the contribution of the major rivers (1,671) with the total flux from this area (2,442). It is evident that Antonov considers that a large proportion of the runoff originates in the smaller rivers.

For the Ob Antonov (1936) gives the amount of heat carried as $4,249 \times 10^{15}$ cal and for the Yenisei $2,849 \times 10^{15}$ cal which gives mean temperatures of 9.6 and 7.0° respectively. Both these rivers have a very large drainage area, reaching far southwards into warmer regions. Lena and Mackenzie have a somewhat cooler drainage area, and all coastal rivers are probably colder. As no better data are available, it seems best to accept Antonov's result for Ob and Yenisei; for Lena and Mackenzie to use an estimated 5° and for the rest of the arctic rivers 3°. Using Antonov's (1958) runoff values this would then lead to a heat transport of $18,413 \times 10^{15}$ cal/year.

IV. PRECIPITATION

The net excess precipitation must be considered as incoming water. The only estimate available is the one by Sverdrup (1954) of 0.09×10^6 m^3/sec or 2,800 km^3/year. It is not certain whether this figure is total precipitation, which is the more likely, or precipitation minus evaporation. Precipitation figures over oceans are very uncertain, and the same holds for arctic areas where most of the precipitation falls as snow. Even more uncertain are the evaporation values for this area. The excess precipitation will be a small residual of two larger quantities. As Sverdrup's estimate is most likely total precipitation, and as this value is very small in comparison to the water transport of the large ocean currents, it seems advisable to disregard this element completely, as long as the estimates of the masses carried by the ocean currents still range over several tens of thousands km^3/year. Furthermore, from energy considerations the contribution of precipitation will be very small indeed, as the temperature difference between precipitation and ocean water is small.

V. DENMARK STRAIT

The most important avenue for outflux from the Arctic Ocean is Denmark Strait. Sverdrup (1954) gives the outflux as 3.55×10^6 m^3/sec or 111,953 km^3/year. Timofeev (1956) gives details of four profiles on which his outflux values are based:

Aug. 13-17/29	11.68 km^3/hr
Mar. 25-28/33	57.92 "
July 30-31/33	2.10 "
Aug. 21-22/33	1.64 "

The difference from one observation to another is very great. Timofeev uses the arithmetic mean and obtains around 161,000 km^3/year. His results, however, could as well be interpreted in other ways. If the March value is taken as the maximum, it could be argued that the minimum is in September with about 2 km^3/hr; the mean would then be about 30 km^3/hr or 262,800 km^3/year. Or it could be assumed that the March value is excessive and the mean value should be taken as 5 km^3/hr or 44,000 km^3/year. Therefore, Timofeev's values allow for a wide margin of mean fluxes.

Treshnikov (1959) gives, without reference, a value similar to Timofeev's, i.e., 162,000 km^3/year. Antonov (1958) quotes, after Chaplygin, 159,500 km^3/year, to which, according to him, has to be added 2,000 km^3 of water which is carried out in the form of ice. The figures of Timofeev, Treshnikov and Chaplygin therefore are in close accord.

The results of Dietrich (1957) can be used to estimate at least the upper limit of the water transport through Denmark Strait. He observed at 60°N, where certainly all water passing through Denmark Strait must pass as well, but where the flux comprises in addition returning warm water masses, which have moved northwards farther to the east. He obtains in the top 1,000 m a southward current of 2.1×10^6 m^3/sec, or 66,226 km^3/year, and below that depth 7.6×10^6 m^3/sec, or 239,674 km^3/year.

Dunbar (1960) gives the flux as 91,454 km^3/year, a value rather low in comparison with the other results mentioned.

For the temperature of this current Model (1950) quotes $+2.0^{\circ}$, Sverdrup (1954) -1.0°. With the cross-section given by Helland Hansen, a mean temperature of $+1.0^{\circ}$ is obtained. Chaplygin (1959) gives the mean temperature along the whole length of the East Greenland current as follows:

60°N	62°	64°	66°	68°	70°	72°	74°	76°	78°	80°N
-1.12°	-1.25°	-1.37°	-1.48°	-1.59°	-1.67°	-1.71°	-1.72°	-1.72°	-1.72°	-1.72°

If the latitude of the Denmark Strait is taken as 68°N, the temperature would be -1.6°. When using Dietrich's results for 60°N (for the upper portion of the current) a mean temperature of $+0.8^{\circ}$ is obtained when allowance is made for the different velocities. This value, referring to June and a more southerly position, is certainly too high. According to Chaplygin's cross-section this figure would have to be reduced by about 0.5°, which would bring the temperature to $+0.3^{\circ}$. Considering all these results, a mean temperature of between 0° and -1° seems the best based assumption for this current.

VI. DAVIS STRAIT

The second channel carrying an outflux from the Arctic Ocean is Davis Strait. Timofeev (1956) obtains this outflux as a residual in his general budget calculation. His figure is 31,400 km^3/year. A further estimate is published by Dunbar (1960), who gives 42,574 km^3/year. Actual observations are published by Smith (1932). The observations used extend over several years. Using his out- and influx figures from the Labrador Sea to Baffin Bay, the net result is 31,536 km^3/year, almost exactly the same as Timofeev's assumption.

The outflux of heat can also be calculated from Smith's results. He gives for the West Greenland current to Baffin Bay 1,576 x 10^{15} cal/year and for the Baffin Island current -3,784 x 10^{15} cal/year. The net result is therefore -2,208 x 10^{15} cal/year.

VII. THE POLAR OCEAN

After having dealt with the currents into and out from the Arctic Ocean, the water exchange with the Polar Ocean will now be discussed.

The Polar Ocean is separated from the rest of the Arctic Ocean by a long stretch of ocean between Novaya Zemlya and Spitsbergen. Most authors are of the opinion that no significant flux takes place across this border. Timofeev (1957) completely disregards any flux east of Spitsbergen. Neither do the ocean current maps published by the British Admirality, nor the ones published in Russia, nor the U.S. Hydrographic Office Atlas (1958), give any influx east of Spitsbergen. Only Zubov-Karelin (after Gordienko 1958) quote a flux of 11,000 km^3/year. It seems best to disregard, for the time being, any flux east of Spitsbergen.

VIII. THE GREENLAND-SPITSBERGEN STRAIT

1. Influx

Zubov-Karelin (after Gordienko 1958) give an influx of 50,000 km^3/year for the warm current between Greenland and Spitsbergen. Timofeev (1957) calculated the influx for the same current to be 94,082 km^3/year on the basis of the following cross-sections: May 1933, June 1939, July 1935, August 1934, December 1936. In 1960 Timofeev revised these estimates and suggested 118,165 km^3/year.

As with the atlantic influx farther south, marked seasonal and annual variations seem to exist. Lee and Hill (1959) state that the flux of the West Spitsbergen current, in the vicinity of Bear Island, was measured thirty times in 1949-1956. The volume transport showed a maximum in January-July and a minimum in September/October -April/May. Antonov (1957), however, states that there is only one maximum (in summer) and minimum (in winter), with the influx varying in the proportion 2:1. Furthermore, he states that the observations indicate an inter-yearly fluctuation of 1:5, i.e., at least of the same magnitude as farther south in the Faeroe-Shetland Channel.

Results from Timofeev (1957) are the only ones available for the temperature of the West Spitsbergen Current. He found the mean temperature to be 1.62°. Timofeev made a detailed analysis of this current, employing temperatures and velocities for each 50 m interval, and in this way he obtained a heat content of 214,357 x 10^{15} cal/year. In a later study Timofeev (1958) remarks that 34% of this heat gain is returned southwards directly by mixing of the water masses of this current with the East Greenland Current. In the authors' opinion this estimate is probably on the high side.

2. Outflux

The outflux of the East Greenland Current between Greenland and Spitsbergen has not been observed. From the influx figures it is estimated by Zubov (1948), without any further reference, as 80,000 km^3/year. Zubov-Karelin (after Gordienko 1958) estimate 86,000 km^3/year, disregarding however the outflux through Davis Strait in their balance. Timofeev (1957), who also obtained the outflux from the influx figures, gives the same as for the West Spitsbergen current, 94,000 km^3/year, evidently balancing the influx from Bering Strait and runoff against the outflux through Davis Strait. This is in disagreement with his results for the Arctic Ocean in 1956. Timofeev (1960) gives the influx from the Norwegian Sea into the Polar Ocean as 118,165 km^3/year. An uncertain check is possible from the results of Dietrich (1957) at 60°N. He obtained an exact balance of in- and outflux from the

Arctic Ocean. If this result, based on one month's observation, can be generalized it would imply two things: 1) The influx through Bering Strait plus runoff from rivers must balance the outflux through Davis Strait. 2) Influx in the West Spitsbergen Current must equal the outflux in the East Greenland Current plus runoff into the Norwegian and Barents Sea. The latter can be calculated, after Antonov (1958), as 512 km^3/year. Under these conditions the outflux of the East Greenland Current would be 93,500 or 117,500 km^3/year, depending on which of Timofeev's figures is accepted.

Temperature data for this current are evaluated by Timofeev (1958). He uses data from seven temperature stations in the current, between 80° and 85°N, obtaining a mean temperature of 0.62°. As no detailed velocity profile is available for this current, he assumes the same velocity profile as for the West Spitsbergen Current. His result (in 1957) was a heat transport of 72,881 x 10^{15} cal/year.

Timofeev's temperature of 0.62° may possibly be too high. His observations were not taken directly in the East Greenland Current, but from an area farther north. They are in sharp contrast to the temperature values given by Chaplygin (1959). According to the latter the temperature at 80°N should be -1.72°. All depends, naturally, on where the main transport takes place, whether near the surface or deeper. If the width of the current is taken, with Zubov, as 200 km and the surface velocity, as determined from the ice drift (Zubov 1948), as 10 km/day, on the assumption of constant velocity downwards a transport of 365,000 km^3/year would result, with a mean depth of 500 m. This figure is obviously too high. It must therefore be assumed that the bulk of the mass transport takes place near the surface. This again would indicate a mean temperature lower than the one used by Timofeev.

A further indication of a lower temperature is the mean temperature for Denmark Strait, which seems to be just above 0°. It can hardly be conceived that the temperature farther north is higher than in the Denmark Strait. It seems, therefore, that a temperature between 0° and -1° would be reasonable.

When comparing the flux data of the strait between Greenland and Spitsbergen with the other in- and outflux observations, the former seem to be considerably less reliable. Practically all figures are based on the one publication by Timofeev, and even his investigations of the West Spitsbergen Current go only to a depth of less than 800 m. However, from the bathymetric map presented by Burkhanov (1956) it is evident that at least one channel in this strait reaches below 1,000 m. This means that nothing is known about the deeper current in this strait. It is therefore not known whether Timofeev's observations, on which all further deductions about in- and outflux are based, really cover the whole flux of the West Spitsbergen Current to the bottom.

The flux and balance calculations for the Polar Ocean must therefore, for the time being, be regarded as only approximate.

IX. ICE EXPORT

A further heat gain for the Arctic Ocean takes place with the formation of ice. All ice exported from the area and not melted again *in situ* represents an actual heat gain for the ocean. Nazarov (1938) estimates the ice volume in the Arctic to be about 32,000 km^3, the winter formation to 13,300 km^3, the melting to 12,000 km^3, with the resulting export of 1,300 km^3.

Zubov (1948) refers to an export estimate of Vize of 8,000 km^3, he himself estimates 3,000 km^3. Gordienko and Laktionov (1960) give a value of 8,000 - 10,000 km^3 of ice exported through the Greenland-Spitsbergen Strait each year.

All estimates are based on considerations of the width of the current, its speed and the mean thickness of ice. The latter is most often taken as 3 m. Timofeev (1960), quoting Gordienko-Karelin's results, gives 2.5 m. All figures mentioned so far refer to the East Greenland Current. It would be necessary to know to which locality the different authors refer: to Denmark Strait or to the strait between Greenland and Spitsbergen. Corton (1954) does not make this distinction as he compares the outflux figures of Sverdrup, referring to Denmark Strait with the ones by Zubov referring to the Greenland Spitsbergen Strait. Nazarov's results probably refer to Denmark Strait, Zubov's to the Greenland-Spitsbergen Strait, as do Vize's figures also. Zubov's claims are based on a width of the ice carrying current of 200 km, and a mean surface speed of 8-12 km/day.

Corton (1954) uses Zubov's figure for the width of the current, and from Sverdrup's mass transport figures he estimates the speed to 20-25 km/day at the surface. When using 20 km/day he obtains a transport of 4,380 km^3/year if the current were completely ice-covered. He assumes then a coverage of 80% and further that only 70% of this is polar ice (the rest from Greenland, etc.). Taking these percentage figures into consideration, he obtains a total export of 2,450 km^3.

Gordienko-Karelin (1945) found large fluctuations from year to year in the ice export between Greenland and Spitsbergen. As an annual average for the period 1933-1944 they give an export of 1,036,000 km^2. With an average thickness of 3 m this would result in 3,108 km^3, with 2.5 m ice thickness, 2,590 km^3.

Gordienko (1958) estimates the width of the East Greenland Current between Greenland and Spitsbergen to be 500 km, much wider than the estimates of Zubov and Corton. This estimate seems to be too large, however, as the whole distance between Greenland and Spitsbergen is less than 600 km, and a portion of this space is occupied by the West Spitsbergen Current. It seems therefore best to accept a mean width of 200 km.

If the export of 1,036,000 km^2 of Gordienko-Karelin took place over a width of 200 km the mean speed, on the assumption of an ice coverage of 80%, would be 17.7 km/day, which is somewhat higher than Zubov's and lower than Corton's estimates. Against these estimates stands Shirshov's (1944) statement that, based on observations from station North Pole (I), the speed in this area is 3.4 miles/day, which is considerably lower than all other estimates.

Koch (1945) sums up all observations of the speed of ice drift. The speed seems to vary considerably, ranging from 5 to 20 miles/day. According to his summary it seems reasonable to accept a speed of 5 miles/day near the shore and about 14 miles/day in the outer part of the ice belt. An average speed of 15-17 km/day seems reasonable.

Finally, it must be mentioned that a much higher estimate of ice export via the East Greenland Current is made by Weaver (unpublished report). He gives a value of 12,500-18,000 km^3/year. He worked with a mean speed of 12 km/day. This estimate appears considerably too high.

At present it seems best to use the value of Gordienko-Karelin as far as the transport of ice is concerned. But Corton's statement, that a certain proportion of the ice originates in Greenland and not in the Arctic Ocean, must be examined. His figure, however, seems very high. Using the glacier discharge from Greenland as given by Bauer (1954) the following figures are obtained:

North Greenland	10 km^3/year
West Coast	90 "
Melville Bay	20 "
East Coast	120 "

Only a part of the North Greenland discharge will appear in the strait between Greenland and Spitsbergen. If 5 km^3 is accepted, which is probably on the high side, this ice can reasonably be disregarded in comparison with the discharge from the Polar Ocean.

The figures so far worked out refer to the Greenland-Spitsbergen Strait. No separate calculations are available for Denmark Strait. It is, however, possible to use the width of the ice flow as given by the U.S. Hydrographic Office (1958) for the different months. Using a speed for the current of 15 km/day, an ice export of 739,125 km^2 would result. As before, an ice cover of 80% of the surface will be accepted. Furthermore, it will be assumed that the mean thickness of the ice in Denmark Strait is less than farther north, as a maximum 2 m. With these figures an ice export of 1,180 km^3/year would result. As this figure is smaller than the flux through the Greenland-Spitsbergen Strait, a loss of heat takes place, and it is not necessary to make a distinction between ice originating in the Polar Ocean and in Greenland.

Weaver (unpublished) is the only author, who stresses also the importance of the ice export via Davis Strait. Weaver gives the speed of the Baffin Bay-Labrador Current as 12.5 miles/day; the U.S. Hydrographic Office uses 0.2-0.3 knots. As Weaver's estimate is rather high, it seems more reasonable to use 10 km/day. Ice is present in the critical area for 10½ months or about 310 days. If, tentatively, an average width of 100 km is assumed, the annual export would amount to 310,000 km^2. On the assumption of 80% ice coverage the actual export would be about 248,000 km^2. From this amount has to be deducted the ice export from Greenland, which is carried by this current. According to Bauer this should amount to 115 km^3. If we assume a mean thickness of 50 m for this land ice, the area will be 2,300 km^2. Thus the export of sea ice would amount to 245,700 km^2. (Assuming an average thickness of 2 m, the annual volume export of sea ice comes to 491 km^3.)

X. HEAT GAIN BY ICE EXPORT

The heat gained in the Arctic by the export of ice depends on the temperature of the ice. This has a pronounced seasonal variation, as shown by all temperature profiles measured in the pack ice (Malmgren 1933, Yakovlev 1955, Untersteiner 1961).

No ice temperature profiles are available from Denmark Strait or the Greenland-Spitsbergen Strait. The latter is near the closed pack ice of the Polar Ocean, an area in which the local temperature variations are relatively small. As a first approximation the temperature observations from the Polar Ocean will be taken to be representative also for the Greenland-Spitsbergen Strait.

The ice temperature profiles in the Polar Ocean depend both on the year of observation and the thickness of ice (Yakovlev 1955). For the present purpose, observations from Malmgren (1933) and Yakovlev (1955) have been used, the former taken in relatively thin pack ice and the latter in a thick ice floe. Thereby an average is obtained which includes at least some of the diverse ice conditions.

The two monthly mean temperatures were averaged from the surface to a depth of 2 m. Thereafter a linear temperature gradient was assumed, to a temperature of -1.8°C at the boundary between ice and water. Mean temperatures were then calculated for the following layers: 0 - 10 cm, 10 - 50 cm, 50 - 100 cm, 100 - 200 cm, 200 cm - water. The following monthly values for ice thickness were used:

cm thickness

	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.
Greenland-Spitsbergen Strait:	275	280	290	295	300	290	275	260	250	255	260	270
Denmark Strait:	225	230	240	245	250	240	225	210	200	205	210	220

It has thus been assumed that the ice thickness in Denmark Strait is 50 cm less than in the Greenland-Spitsbergen Strait. It would be very valuable to have actual observations of these thicknesses, or more accurate estimates.

Concerning ice temperatures in Denmark Strait, no estimates are available. Therefore, the mean temperatures for Angmagssalik were used as surface temperatures. These are screen temperatures and certainly higher than the surface temperatures. However, the ice of the East Greenland Current extends for a considerable distance from the coast, and the temperatures should rise to the east. This may compensate for the use of Angmagssalik temperatures.

The temperature of the water in Denmark Strait, at the ice-water boundary, was taken as $-1.6^{\circ}C$.

The following values were used for the salinity of the ice (see Untersteiner, 1961):

	0-10 cm	10-50 cm	50-100 cm	100-200 cm	200 cm-water
Greenland-Spitsbergen Strait:	0.2 ‰	0.6 ‰	1.5 ‰	2.5 ‰	3 ‰

	0 cm - water
Denmark Strait:	1.5 ‰

Although many of the above values are uncertain, nevertheless with these data it is possible to obtain an estimate of the heat released by the formation and cooling of sea ice.

Malmgren's equation for the freezing sea water is

$$L = L_p \left(1 - \frac{S_i}{S_w}\right)$$

where L, L_p are the latent heats of fusion of sea ice and pure ice, and S_i, S_w are the salinities of the sea ice and sea water.

The heat required to raise the temperature of 1 cm^3 ice is, after Untersteiner (1961):

$$Q = \rho \Delta T(0.5 + \frac{4.1S}{T_1 T_2})$$

where:

Q = heat required to raise the temperature of 1 cm^3 ice by an amount ΔT
ρ = density of ice: 0.913 g/cm^3
T_1 and T_2 = ice temperatures: ($T_2 - T_1 = \Delta T$)
S = Salinity of the ice in $^{o}/oo$.

With these formulae the amount of heat liberated by the ice layer existing in a particular month was calculated for 1 cm^2 ice surface. The results are as follows:

	cal/cm^2	
	Greenland-Spitsbergen Strait	Denmark Strait
January	22,426	17,039
February	23,040	17,512
March	23,861	19,118
April	23,849	18,145
May	23,372	17,032
June	21,912	16,351
July	17,801	15,329
August	17,508	14,307
September	17,804	13,626
October	18,860	14,699
November	20,275	14,578
December	21,829	15,102
Year	21,045	16,070

No reference has been found in the literature to monthly or seasonal fluctuations in ice discharge. It would seem likely that a significantly higher export should take place during summer, when the ice is less densely packed and has more freedom of movement, then in late winter when open leads refreeze almost immediately. If this reasoning were correct, the movement of the ice floe stations in the Polar Ocean should show a similar seasonal variation.

An examination of the drift data obtained on Station Alpha (Reed and Campbell, 1960) gives the following results:

	Mean drift speed (knots)
July 1957	0.25
August	0.22
September	0.16
October	0.23
November	0.15
December	0.10
January 1958	0.15
February	0.10
March	0.11
April	0.06
May	0.11
June	0.13
July	0.12
August	0.11

mean speed for the whole period = 0.14 knots = 6.2 km/day.

Information on the drift of some of the Russian "North Pole" Stations, contained in Gordienko (1958) and Gordienko and Laktionov (1960), may be summarized as follows:

		mean drift speed km/day	(true distance) km/day
N.P. I	June 1937 - February 1938	7.5	
N.P. II	April 1950 - April 1951	6.9	
N.P. III	April 1954 - April 1955	4.9	
	April 15 - June 20, 1954		2.4
	June 20 - September 20, 1954		3.8

(cont'd. next page)

N.P. IV	April 1954 - April 1955	6.8	
	April 8 - June 21, 1954		4.5
	June 21 - September 20, 1954		4.3
N.P. IV	April 1955 - April 1956	6.8	
	April 10 - August 8, 1955		3.3
	August 8 - September 30, 1955		4.2
N.P. IV	April 1956 - April 1957	5.3	
N.P. V	April 1955 - April 1956	6.9	
	April 20 - September 21, 1955		3.8
	April - October 1956		6.4
N.P. VI	April 1956 - April 1957	7.1	
	April 1957 - April 1958	7.2	
	April 1958 - April 1959	6.8	
	April - September 1959		6.2
N.P. VII	April 1957 - April 1958	5.4	
	April 1958 - April 1959	4.4	
N.P. VIII	April 1959 - April 1960	7.3	
	Mean Speed (not including N.P. I):	6.3	4.3

These figures indicate that the mean annual drift speed is about 6.3 km/day (true distance), and the drift varies markedly both from month to month and also from year to year. There is no indication that the summer drift is faster than the winter drift. As far as the outflux straits are concerned, there would still be the possibility that the width of the straits is diminished by landfast ice. As no observations are available of the varying extent of the shore ice, it is assumed that a uniform distribution of ice export during the year comes close to the actual conditions.

Thus, the total yearly ice export is multiplied by the mean annual figure for heat release.

The results are, if for Davis Strait the same heat content is used as for Denmark Strait:

Heat gain by ice export via

Greenland-Spitsbergen Strait:	218,026 x 10^{15}cal
Denmark Strait:	95,022 x 10^{15}cal
Davis Strait:	39,484 x 10^{15}cal

The heat gain for the Polar Ocean should therefore be 257,510 x 10^{15}cal, and for the whole Arctic Ocean 134,506 x 10^{15} cal, this figure being smaller as considerable melting takes place in the Norwegian Sea. The heat loss for this sea, due to melting of imported ice would be 123,004 x 10^{15}cal.

XI. WATER BALANCE AND HEAT FLUX

After having discussed the individual currents, an attempt will now be made to arrive at a water balance and a heat flux estimate.

Tables 1a and 1b give summaries of the different flux observations. Figures in round brackets are ones which do not apply directly to the heading of the column. [ ] indicate that from the evidence available the given values seem definitely too high or too low and can be excluded from further consideration.

Table 2 gives those maximum and minimum values for each current, which seem reasonably well substantiated. From the summing of these figures it seems likely that the extreme values of the deficit side must be too high.

The last sum in Table 2 refers to the above mentioned result by Dietrich, that the influx and outflux in the Atlantic sector seems to be balanced or very nearly so, which means that the Σ Bering Strait + runoff must nearly balance outflux through Davis Strait. When comparing these maximum and minimum figures, the maximum for Davis Strait seems good and the minimum somewhat low.

This portion of the balance sheet can be narrowed still further, as the runoff figure of Antonov (3,800 km^3/year) seems to be the best and should be accepted. Of the Bering Strait figures (Table 1a), observations 5, 6 and 7 all seem well substantiated by observations and none merits preference. It seems therefore best to accept for the time being an average of these three, i.e., 32,500. If these values are accepted, the outflux via Davis Strait should be taken as 36,300 km^3/year.

A value for Atlantic Ocean and Denmark Strait has to be found. Values 1 and 9 (Table 1a) for the Atlantic must be discarded, as they are below the lowest likely estimate for Denmark Strait. The value certainly has to be above 100,000. For Denmark Strait, all Russian authors agree on a value around 160,000. Unfortunately, the observational material on which their assumptions are based is known only for Timofeev's results. His value is, as already mentioned, to a large extent influenced by one cross-section with a high value. The Russian estimates for the Atlantic, on the other hand, are all lower than 160,000. From the Russian results the most likely flux figure is 140,000, while the most likely figure obtained from other sources would be 112,500.

These considerations are valid as long as Dietrich's balance result is taken to be representative. On the assumption that the balance in the Atlantic Ocean need not be kept, one would probably arrive at slightly different figures.

All these possibilities are summarized in Tables 3. A first glance at these tables shows the still remarkable differences. The main reason for these discrepancies will, in the authors' opinion, chiefly be found in the fact that the oceanic observations extend over short periods and are not synoptic. The great differences in the seasonal and yearly fluctuations do in fact not permit strict comparisons to be made between the different sets of observations. However, until many more simultaneous observations become available, one must try to use the figures above.

When using the temperatures evaluated in the preceding paragraphs for the different currents, the mass flux figures can be transformed into heat fluxes. These are summarized in Table 4 for the Arctic and Polar oceans, and the heat gain by ice formation is also considered. From this table it will be seen that the different assumptions about the flux of atlantic water amount to a difference of 17-20% in the heat gain per cm^2 for the Arctic Ocean. Less serious is the difference in assumed water temperature, which produces a difference of about 10% in the heat gain per cm^2.

These differences are more important for the Arctic Ocean as a whole than for the Polar Ocean. There, about half of the total heat gain arises from the formation and export of ice. A wrong estimate of the ice export will be felt seriously.

TABLE 1a

ARCTIC OCEAN

Flux km^3/year

	Bering St.	Atlantic	Runoff	Precip.	Denmark St.	Davis St.
1. Sverdrup	[9,400]	94,500	[5,000]	2,800	112,000	
2. U.S. Coast Guard	[28,000]					
3. Zubov-Karelin	[20,000]					
4. Wolkov	[21,000]					
5. Basakov	36,000					
6. Maksimov	30,300					
7. Coachman	31,500					
8. Treshnikov	37,500	128,500		700	162,000	
9. Dunbar		94,500			[91,500]	42,500
10. Jacobson		[166,000 [130,000]]				
11. Tait		113,000 [90,000]				
12. Dietrich		[(214,500)]			[(240,000)]	
13. Timofeev		[213,000] 152,000	4,400		161,000	
14. Shokalskii		140,000				
15. Gordienko			3,000			
16. Antonov			3,800			
17. Chaplygin					160,000	
18. Smith						31,500
19. Antonov (58)	37,500	[213,000]				

TABLE 1b

POLAR OCEAN

Flux km^3/year

(only values which differ from Arctic Ocean are given)

	East of Spitsb.	West of Spitsb.	East Greenl.	Runoff
Zubov-Karelin	11,000	50,000	86,000	
Timofeev		117,500 93,500	93,500	
Zubov			80,000	
Antonov		128,500		3,300

TABLE 2

ARCTIC OCEAN

Flux km^3/year

	Influx			Outflux	
	Bering St.	Atlantic	Runoff	Denmark St.	Davis St.
Maximum	37,500	152,000	4,400	162,000	42,500
Minimum	30,000	94,500	3,000	112,000	31,500

Σ	Maximum	194,000	Σ	Maximum	204,500
Σ	Minimum	127,500	Σ	Minimum	143,500

Σ Bering St. + Runoff 42,000 Maximum

33,000 Minimum

TABLE 3a

PROBABLE ANNUAL WATER AND HEAT BALANCE - ARCTIC OCEAN
(excluding ice)

		km^3	^oC	$cal x 10^{15}$
A.	Bering Strait	32,500	0.93	+30,225
	Atlantic (Russian est.)	140,000	7.8	+1,092,000
	Runoff	3,800	9.6, 7, 5, 3	+18,413
	Denmark Strait	140,000	0, -1	0 (a) -140,000 (b)
	Davis Strait	36,300		-2,541

Σ heat gain a) +1,143,179 or b) +1,283,179

		km^3	^oC	$cal x 10^{15}$
B.	Bering Strait	32,500	0.93	+30,225
	Atlantic (European est.)	112,500	7.8	+877,500
	Runoff	3,800	9.6, 7, 5, 3	+18,413
	Denmark Strait	112,500	0, -1	0 (c) -112,500 (d)
	Davis Strait	36,300		-2,541

Σ heat gain c) +928,679 or d) +1,041,179

Negative values in column 3 indicate flow of water at a temperature less than 0^oC.

TABLE 3b

PROBABLE ANNUAL WATER AND HEAT BALANCE - POLAR OCEAN
(excluding ice)

	km^3	$^{\circ}C$	$cal \times 10^{15}$	
Bering Strait	32,500	0.93	+30,225	
West Spitsbergen	93,500 117,500	1.62	+151,470 +190,350	(e) (f)
Runoff	3,300		+16,100	
Davis Strait	36,300		-2,541	
East Greenland	93,500 (117,500)	-0.5	-46,750 (-58,750)	(e) (f)

Σ heat gain e) +247,086 or f) +297,966

TABLE 3c

PROBABLE ANNUAL HEAT BALANCE NORWEGIAN - BARENTS SEA
(excluding ice)

	$cal \times 10^{15}$	
Influx from Atlantic	+1,092,000	(Russian est.)
	+877,500	(European est.)
Influx from Polar Ocean	-46,750	
Influx from Runoff	+2,300	
Σ influx	+1,047,550	(Russian est.)
or	+ 833,050	(European est.)
Outflux to Polar Ocean	+151,470	
Outflux to Atlantic	-140,000	(Russian est.)
	-112,500	(European est.)
Σ outflux	+11,470	(Russian est.)
or	+38,970	(European est.)

Σ heat gain $+1,036,080 \times 10^{15}$ cal or 24,763 cal/cm^2 (Russian est.)

or $+794,080 \times 10^{15}$ cal or 18,979 cal/cm^2 (European est.)

TABLE 4

TOTAL HEAT GAIN, AND HEAT GAIN PER cm^2

Annual

A. Arctic Ocean

	gain by currents $cal \times 10^{15}$	gain by ice $cal \times 10^{15}$	total heat gain $cal \times 10^{15}$	gain per cm^2 Cal.
a.	1,143,179	134,506	1,277,685	9,068
b.	1,283,179	134,506	1,417,685	10,062
c.	928,679	134,506	1,063,185	7,546
d.	1,041,179	134,506	1,175,685	8,344

B. Polar Ocean

e.	247,086	257,510	504,596	5,094
f.	297,966	257,510	555,476	5,607

a. based on Russian estimates of Atlantic flow, and a water temperature of 0°C in Denmark Strait.

b. as above, with a Denmark Strait water temperature of -1°C.

c. based on European estimates of Atlantic flow, and a water temperature of 0°C in Denmark Strait.

d. as above, with a Denmark Strait water temperature of -1°C.

e. based on West Spitsbergen current transport of 93,500 km^3/year.

f. based on West Spitsbergen current transport of 117,500 km^3/year.

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